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# An Assessment of Near Surface Biological Volume Scattering Off the Continental Shelf of Virginia

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91-10758

## ABSTRACT

Acoustic models were used to estimate volume scattering from fish and marine mammals in the vicinity of the Surface WAves Dynamics Experiments (SWADE) at 37.5°N and 74°W as part of planning for the Office of Naval Research Acoustic Reverberation Special Research Project (ARSRP) sea surface scattering experiment. Animal densities were derived from fisheries assessments and airborne surveys of marine mammals. Animal target strengths were based on resonant models of fish with swimbladders, bent cylinder models of fish without swimbladders, and in situ measurements of mammals. Estimates of scattering were made for a broad frequency range of 10 Hz to 10 kHz with emphasis placed on the planned experimental frequencies of 100 Hz to 800 Hz. Average layer scattering strengths calculated for average densities of animals at two potential experimental sites ranged from -74 to -53 dB between 100 and 800 Hz. Since most fish and marine mammals will be aggregated to some degree, volume scattering can be expected to vary within the area insonified during ARSRP measurements. A model of fish school encounter suggests that only aggregations of porpoise, mesopelagic fish and nonswimbladder bearing fish are widespread enough to produce consistent reverberation, producing layer strengths slightly above -80 dB. Given the variations with frequency, location, time of day, and uncertainties of animal distribution, layer strengths at the experimental sites are expected to be between -80 and -50 dB. The fish school encounter model also suggests that target strengths and numbers of swordfish schools and whales are high enough to cause a strong discrete echo every several hours; while herring, bluefish, hake, and tuna schools will cause discrete echoes at time scales of hours to days. Estimates of surface scattering based on relationships reported by R. P. Chapman and J. H. Harris (1962, Surface backscattering strengths measured with explosive sound sources. J. Acoust. Soc. Am. 34:1592-1597) indicate that near surface biological scattering will interfere with measurements of surface scattering at shallow grazing angles.

# ACKNOWLEDGMENTS

The authors are indebted to numerous people at the National Marine Fisheries Service laboratories in Beaufort, NC, Miami, FL, Pascagoula, MS, and Woods Hole, MA, for providing us with publications, documents, and data. H. Deferrari was instrumental in providing specifications on his acoustic array. The authors thank M. Wilson for programming the model of swimbladder resonance and C. Levenson for making constructive comments on the manuscript. This work was funded by Program Element 61153N of the Office of Naval Research Acoustic Reverberation Special Research Project, Marshall Orr, Program Manager.

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# AN ASSESSMENT OF NEAR SURFACE BIOLOGICAL VOLUME SCATTERING OFF THE CONTINENTAL SHELF OF VIRGINIA

## INTRODUCTION

The performance of long range low frequency active sonar systems can be limited by reverberation from the sea surface. Thus, the goal of the air/sea component of the Office of Naval Research (ONR) Acoustic Reverberation Special Research Project (ARSRP) is to develop an understanding of the physics of low grazing angle acoustic backscatter from the ocean surface at various sea states through the conduct of a theoretical and experimental research program. The first ARSRP acoustic surface scattering experiment was scheduled from December 1990 to March 1991 in 2000 to 3000 m of water off the coast of Virginia as part of ONR's Surface WAve Dynamics Experiment (SWADE). The transmitter and receiving array were to be moored at approximately 200 m depth. Once each hour, a variety of pulses up to 1 second in length were to be transmitted to examine surface backscattering at grazing angles of 2° to 12° at frequencies between 100 and 800 Hz.

Acoustic scattering near the sea surface can be attributed to three mechanisms: the wind roughened sea surface; elements injected into the sea surface, such as bubbles; and marine animals, which often inhabit the near surface zone. In some areas and seasons, resonance scattering from the swimbladders of relatively high numbers of large fish dispersed within the upper 100 m of the water column has been found to produce low frequency volume reverberation levels that exceed low grazing angle surface reverberation levels, so that measurements of surface scattering would have been impossible. Also, fish schools or pods of marine mammals can cause clutter or discrete echoes that can interfere with surface scattering measurements.

Although there was no indication that high numbers of large fish were to be expected in the area of the first ARSRP acoustic surface scattering experiment, volume reverberation, clutter, or discrete echoes caused by near surface animals were still potential sources of confusion in the interpretation of experimental results. The goals of this assessment were to reduce this possible confusion by estimating the expected biological scattering in the area prior to the experiment, to provide information for experiment planning, and to establish the background for a comparison of predicted and measured biological scattering. Direct measurements of volume scattering were to be obtained from a horizontally directed beam of the ARSRP array during the experiment.

## BACKGROUND

Two possible experimental sites were under consideration during planning: A near-shelf site at about 37°19' N, 74°00' W, near the SWADE Woods Hole Oceanographic Institution (WHOI) buoy and an off-shelf site at about 37°08' N, 73°38' W, near the SWADE DISCUS-E buoy (Fig. 1). These sites are within 25 to 75 km of the 200 m edge of the continental shelf. This close proximity to the shelf necessitated the consideration of fauna that occur at the shelf break, on the slope, and over deeper waters (Fig. 2). The region represents a junction between shallow, productive shelf waters with strong seasonal thermal variation, and deeper slope waters of relative thermal consistency and lower productivity. In addition, the Gulf Stream passes just east of the sites. These diverse features are reflected in the biology of the region.

Biota of the shelf and slope are closely linked (Backus, 1987; Milliman and Wright, 1987). For example, in summer, many open ocean pelagic species migrate into and through the shelfbreak region in search of the rich food resources found on the warm productive shelf. When these waters cool, many of these fish move offshore to overwinter in warmer waters that occur near the shelf break and slope. The timing and extent of these migrations are believed to depend on the position and strength of both the Gulf Stream and shelf-break fronts (Casey et al., 1987). The relationship between these warmer offshore waters and the experimental sites is shown in Figure 3. Checkley et al. (1988) suggest that a number of fish have evolved to reproduce in winter at the western edge of western boundary currents such as the Gulf Stream and Kuroshio. Whether such offshore spawning occurs in the vicinity of the ARSRP experimental sites is not known.

Quantitative information on the distribution and abundance of fish beyond the shelf break is limited. The major fisheries in the region are: (1) a trawl fishery on the shelf; (2) a sport fishery on the shelf; and (3) a longline fishery off the shelf. Much of the assessment of commercial species is directed at populations on the shelf by a National Marine Fisheries Service (NMFS) bottom trawl program, which uses gear that is limited to depths shallower than 300 m. As a consequence, the offshore distribution of many fish species is unclear. NMFS winter distribution maps show that some species have high abundances up to and including the shelf break but the extent these fish occur in deep water beyond the shelf break is limited to anecdotal information obtained from commercial fisherman (Bigelow and Schroedér, 1953).

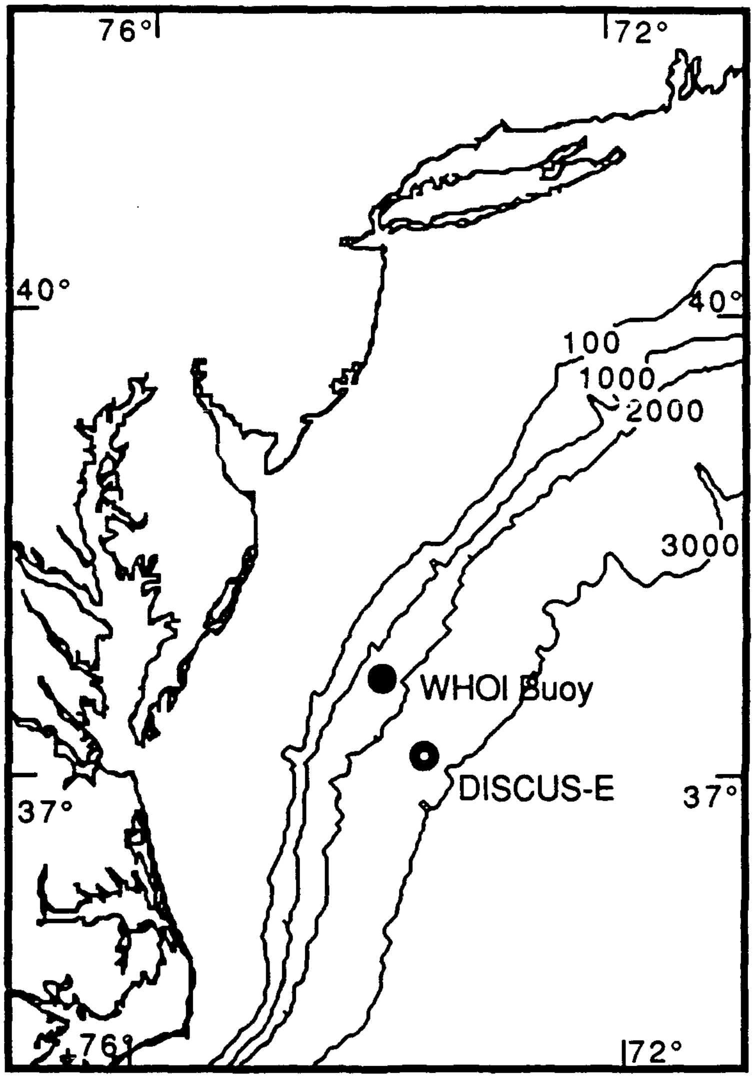



Figure 1. Location of two tentative ARSRP sites in relation to the shelf slope bathymetry of the region.

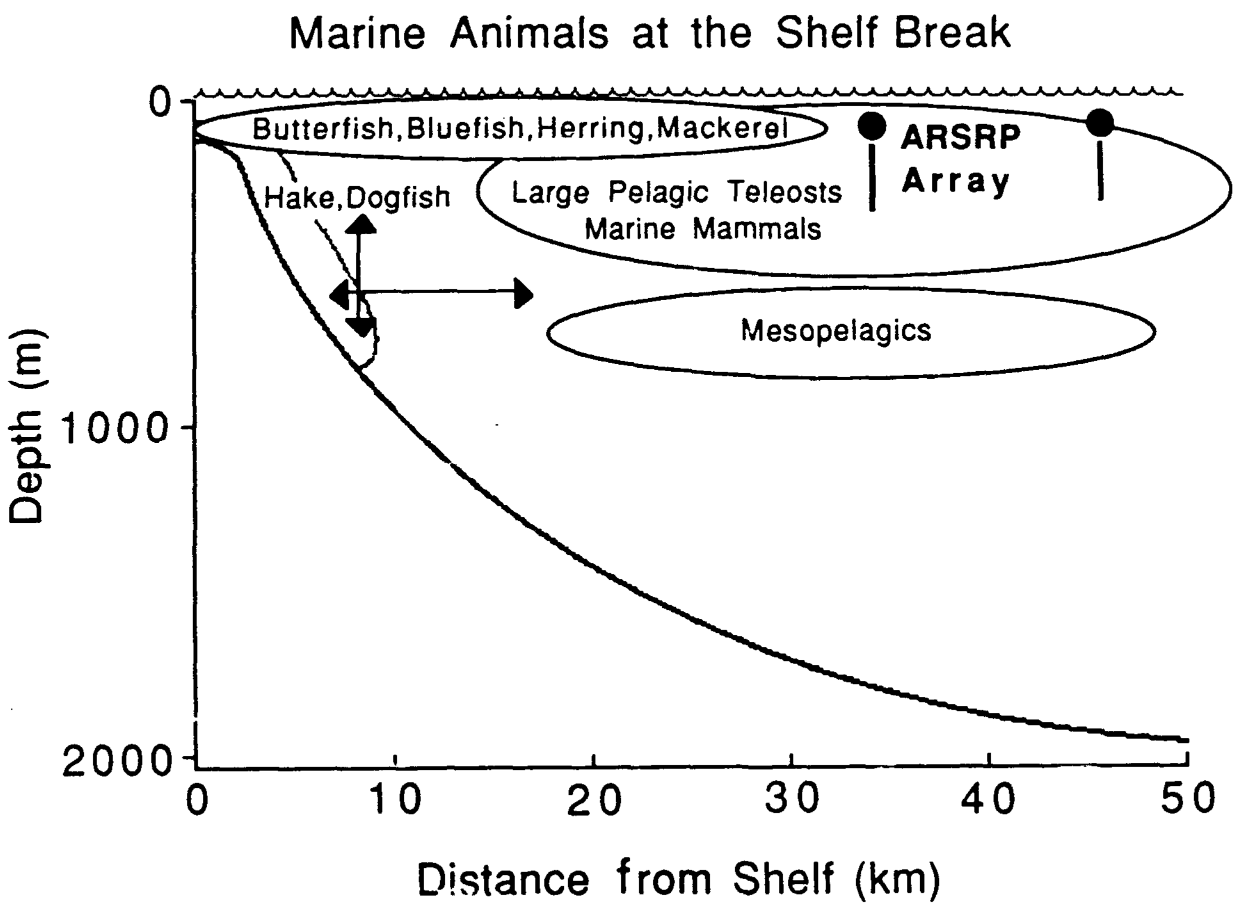



Figure 2. Diagrammatic cross section of the shelf break and slope off Virginia illustrating two potential positions of the ARSRP array in relation to fish and marine mammals.

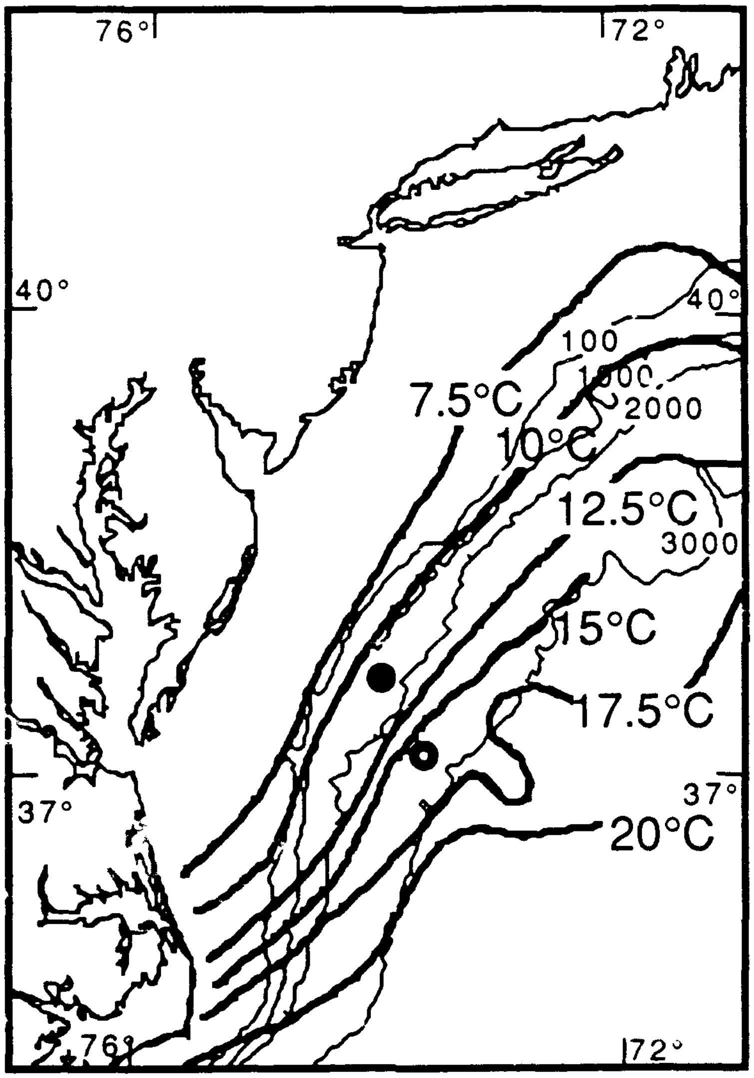



Figure 3. Sea surface temperature in January (after CEQ/CZM, 1980).

Farther offshore, large pelagic predators are caught by an extensive longline fishing effort aimed primarily at swordfish and yellowfin tuna. Rough estimates of the numbers of these fish near the experimental sites can be derived from catch records of this fishery. Because the gear used is selective for large pelagic predators, it does not provide any information on the occurrence of smaller fish.

Little is known about the distribution, abundance, and habits of the deep ocean community on the continental slope. The region contains members of the mesopelagic fish community that occasionally become concentrated at very high densities (Backus et al., 1968). In addition, large congregations of krill recently have been found in the submarine canyons off Georges Bank (Greene et al., 1988). These populations are presumably associated with the high productivity of the shelf. They are likely preyed upon by fish occurring on the slope. Similar concentrations of krill and fish could occur farther south, near the experimental sites.

Information on the distribution and abundance of porpoise and whales is available from a compilation of aircraft and ship surveys off the east coast of the United States (CETAP, 1982). These mammals prey on small fish and invertebrates associated with hydrographic features of the shelf break and slope and are found in the area throughout the year. They are most abundant in summer, but are found in midwinter in appreciable numbers and are expected within the vicinity of the experimental sites.

The fact that fish and mammals rarely occur at average densities compounds the uncertainties caused by limited knowledge of the numbers and offshore distribution of pertinent species. Marine mammals travel in small pods or as individuals. Fish are patchy in distribution, occurring in various types of aggregations (Norris and Dohl, 1979; Pitcher, 1986). Even the most loosely dispersed fish generally occur in large shoals extending from several to tens of kilometers. More sociable species often will be found tightly packed into schools. The fish density within these schools can be high, since each fish only requires a volume proportional to its body length cubed (Pitcher and Partridge, 1979). For most species, good quantitative measures of expected school or shoal sizes and the numbers of fish contained within these aggregations are lacking. Often, anecdotal observations or data on similar species must be relied upon.

Patchiness in animal distributions will obviously change the character of scattered returns from the volume. The scale of areal inhomogeneity relative to the size of the insonified area will determine what the changes are. Large scale patchiness will cause spatial variations in volume reverberation; small groups of animals can cause clutter, while bigger groups can cause discrete echoes. The transition from reverberation to clutter to discrete echoes is continuous and decisions as to where the transitions occur is a matter of personal bias and system characteristics.

In order to achieve the goal of estimating potential biological scattering, pertinent scattering species were determined and given the limitations on available data, their winter distributions, abundances, size ranges, and depths were estimated as accurately as possible from assessments and surveys. Bioacoustic algorithms were then used to calculate target strengths of individual fish or marine mammals as functions of frequency. Two separate modeling avenues were then followed. The first assumed that all animals were uniformly distributed in layers and an average layer volume scattering strength was calculated for each species and in turn, for all species present at a particular ARSRP site. The second assumed that all species aggregated into schools or pods and the target strength and likelihood of occurrence of an average school of fish or a pod of marine mammals were calculated. Hence, the first avenue assumes that all animals contribute to volume reverberation and the second assumes that they all cause clutter or discrete echoes. The results obtained following each avenue were then compared and final estimates of the effects of biological scattering were determined. No attempt was made to determine if any biological scattering predicted would actually produce reverberation, clutter, or discrete echoes at the ARSRP array because an examination of other relevant terms in the active sonar equation was beyond the scope of this study.

## SCATTERERS

### Shelf/Slope Stocks

Fish distribution maps and species accounts (Almeida et al., 1984; CEQ/CZM, 1980; Grosslein and Azarovitz, 1982) indicate that there are six major groups of commercial stocks occurring on the continental shelf and slope which could occur in pelagic waters far enough off the shelf to produce significant near surface volume scattering at the ARSRP sites. Total stock sizes of these six commercial fish groups are reported in Table 1. These estimates were determined from recent fisheries stock assessments on the shelf (NOAA, 1989). The first two groups are Atlantic herring, *Clupea harengus harengus*, and bluefish, *Pomatomus saltatrix*, both possessing swimbladders. The third group is a complex of five hake species: *Merluccius capensis*, *Merluccius albidus*, *Urophycis tenuis*, *Urophycis regia*, and *Urophycis chuss*, all of which possess swimbladders. The final three groups are nonswimbladder bearing fish. These are

Table 1. Estimation techniques and density of potential contributors to volume backscattering at the near-shelf and off-shelf ARSRP sites.

| Species/Group | Data Source | Stock (MT) | Density (no./km$^2$) | |
|---|---|---|---|---|
| | | Shelf | near-shelf | off-shelf |
| Mesopelagics | Midwater Trawl[a] | | 1,000,000 | 1,000,000 |
| Hake | Stock Assessment[b] | 142,000 | 1,200 | 120 |
| Atlantic herring | Stock Assessment[b] | 180,000 | 4,000 | 400 |
| Bluefish | Stock Assessment[b] | 80,000 | 110 | 11 |
| Butterfish | Stock Assessment[b] | 20,000 | 330 | 33 |
| Atlantic mackerel | Stock Assessment[b] | 1,800,000 | 18,000 | 1,800 |
| Spiny dogfish | Stock Assessment[b] | 600,000 | 240 | 24 |
| Tuna | Stock Assessment[c] | | 0.082 | 0.082 |
| Swordfish | Stock Assessment[c] | | 0.43 | 0.43 |
| Porpoise and sm. Whales | Aircraft Survey[d] | | 0.3 | 0.3 |
| Medium Whales | Aircraft Survey[d] | | 0.04 | 0.04 |
| Large Whales | Aircraft Survey[d] | | 0.001 | 0.001 |

[a]R. H. Love, unpublished data.
[b]NOAA (1989)
[c]ICCAT (1989)
[d]CETAP (1982)

Atlantic mackerel, *Scomber scombrus*, spiny dogfish, *Squalus acanthias*, and butterfish, *Peprilus triacanthus*. These nonswimbladder groups all comprise a major part of the commercial catch and are included in the analysis because of their high abundance and potential contribution as non-resonant low frequency scatterers when schooling. Butterfish do contain a swimbladder in the juvenile form but it is regressed in mature fish (Horn, 1975), which would most likely be encountered off the shelf. Winter distributions of these six groups are based on NMFS surveys and are shown in Figures 4 through 9. These maps show that all species are found at high numbers at the shelf break, which is the offshore limit of the surveys. All of these fish are probably found farther offshore pursuing either prey or warmer water during winter months (Grosslein and Azarovitz, 1982; CEQ/CZM, 1980).

Herring generally occur in large diffuse layers at night, at 20 to 200 m depth. During day they aggregate into compact schools at depths of 100 to 200 m. Based on data reported by Anthony and Fogarty (1985) for the Gulf of Maine, Atlantic herring appear to range from about 8 to 34 cm length with the mode at 12 cm. The size and shape of herring schools are highly variable, ranging from small compact schools of 850 $m^2$ extent and 67,000 fish to large diffuse shoals of 20 $km^2$ extent and 97 x $10^6$ fish (Buerkle, 1987; Misund and Ovredal, 1988). Medium size shoals of $10^6$ fish and 2 $km^2$ extent were used in the analysis.

Bluefish are near-surface pelagic fish, ranging from the surface to 50 m both day and night. Bluefish range in size from 22 to 76 cm at ages of 1 and 8 years, respectively, with the mode at about 35 cm (NOAA, 1989; Bigelow and Schroeder, 1953). Quantitative information on school sizes and numbers per school is wanting. However, assuming behavior similar to that of tuna and mackerel, other nearsurface predators, there would be roughly 50,000 fish in a typical flat disc shaped school about 2,000 $m^2$ in extent (Table 2).

The five species of hake are all demersal fish, living near the bottom on the shelf and slope. For example, Figure 6 shows the distribution of silver hake, *Merluccius capenis*, which has been found up to the edge of the shelf-break in late winter. Anecdotal evidence suggests many species of hake occur down to depths of 1000 m (Bigelow and Schroeder, 1953). At night, hake make vertical migrations of several hundred meters in search of midwater prey, typically small invertebrates or larval and juvenile fish (Bigelow and Schroeder, 1953). The near-shelf ARSRP site is at 1800 m, still beyond the supposed distribution of hake. However, observations of

Atlantic Herring

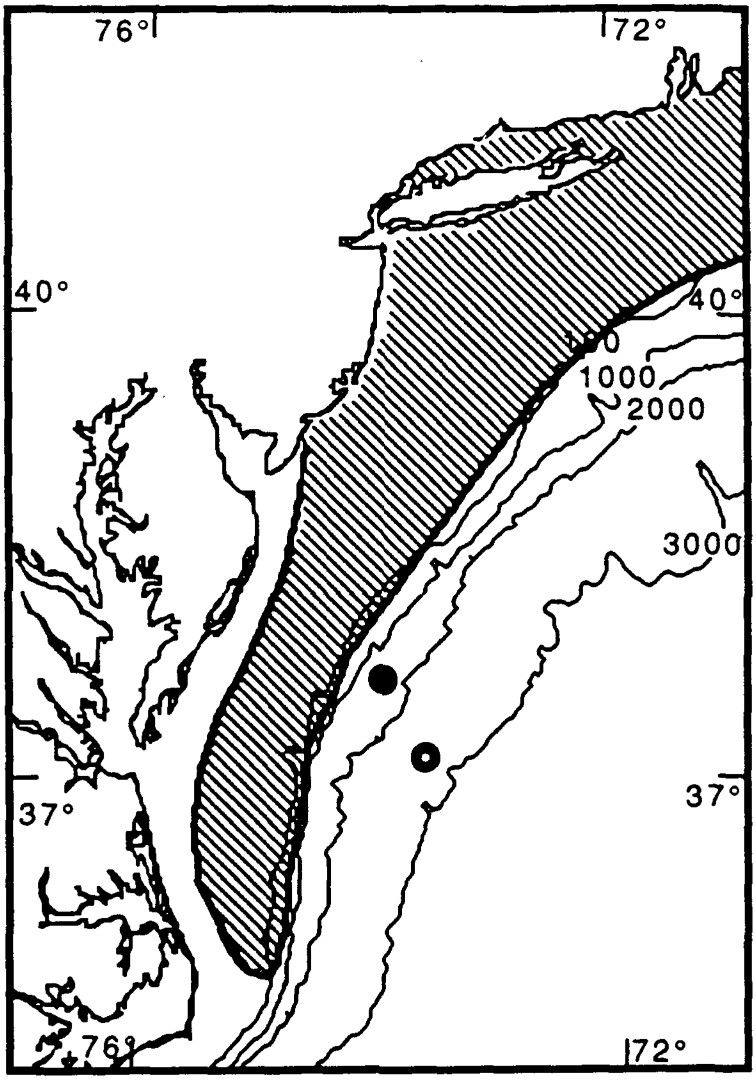



Figure 4. Winter distribution of Atlantic herring, *Clupea harengus harengus* (after CEQ/CZM, 1980).

Bluefish

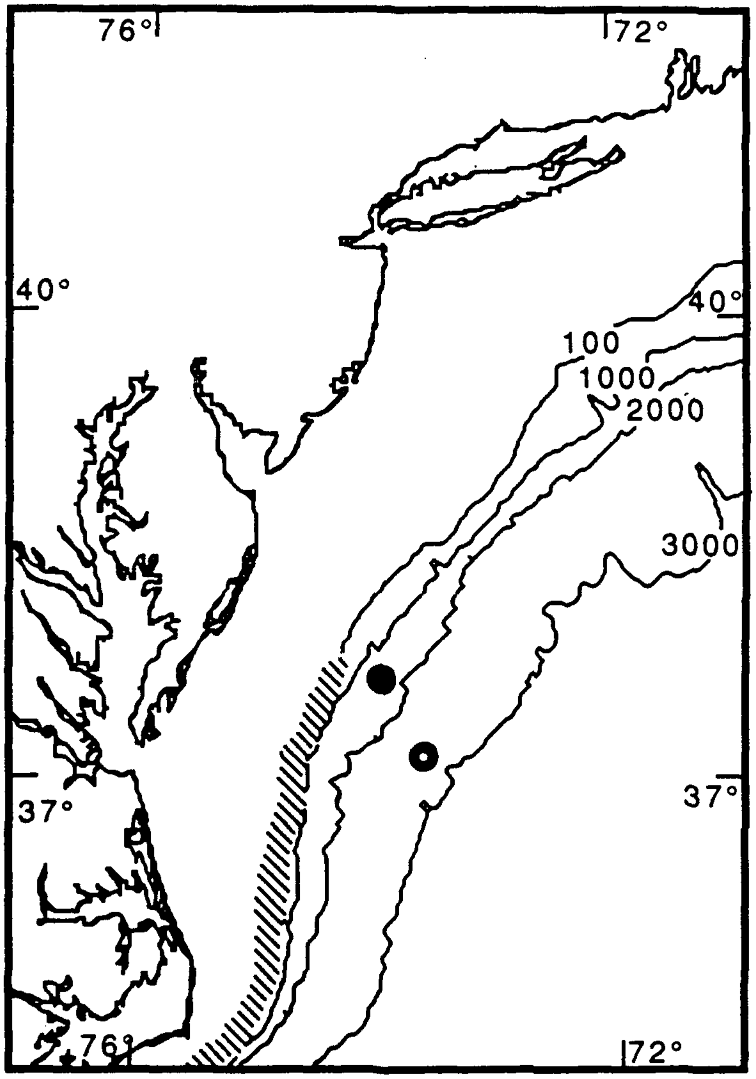



Figure 5. Winter distribution of bluefish, *Pomatomus saltatrix* (after CEQ/CZM, 1980).

Silver Hake

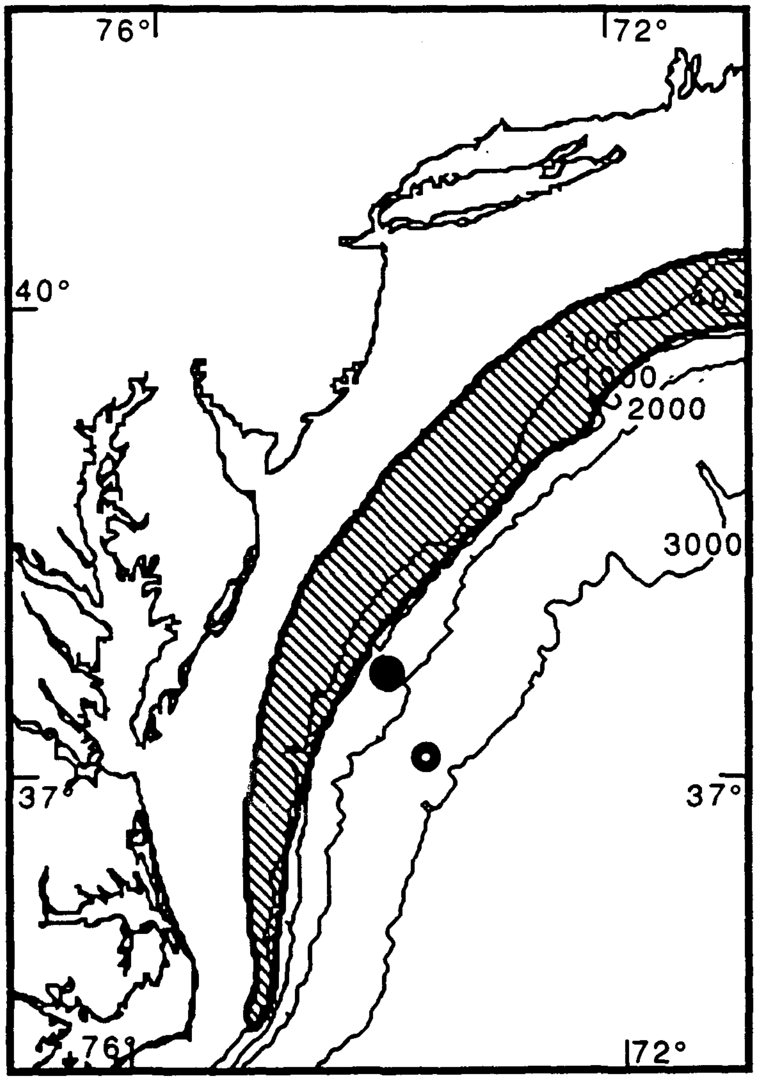



Figure 6. Winter distribution of silver hake, *Merluccius capensis* (after CEQ/CZM, 1980).

# Butterfish

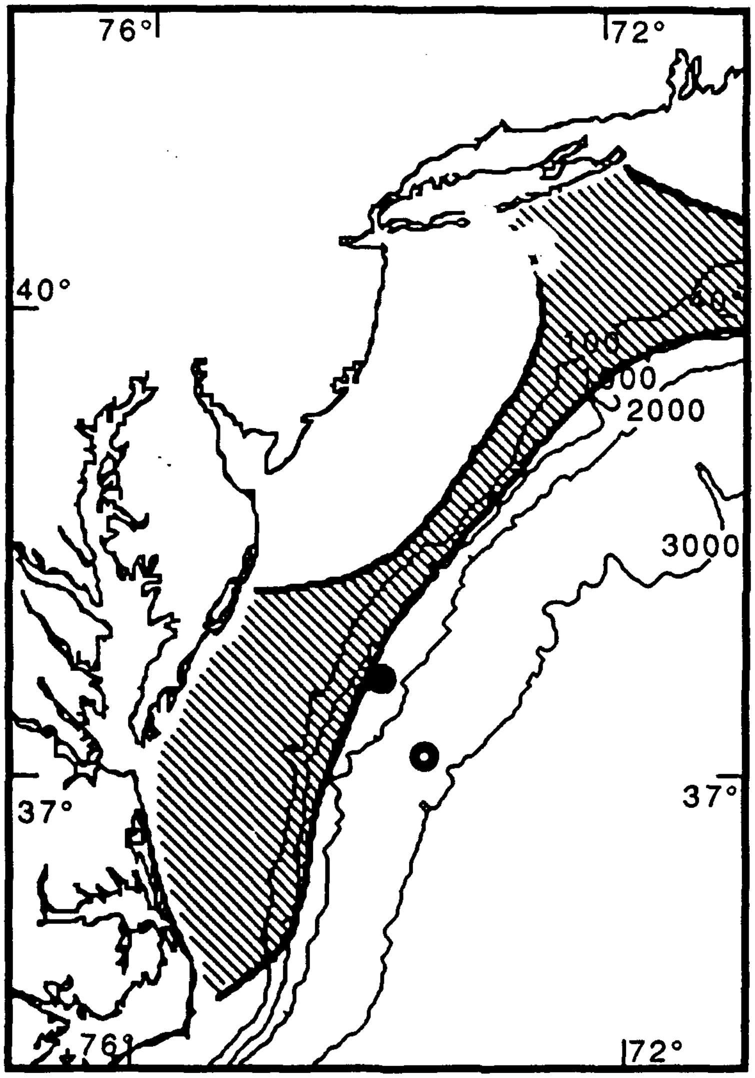



Figure 7. Winter distribution of butterfish, *Peprilus triacanthus* (after CEQ/CZM, 1980).

Atlantic Mackerel

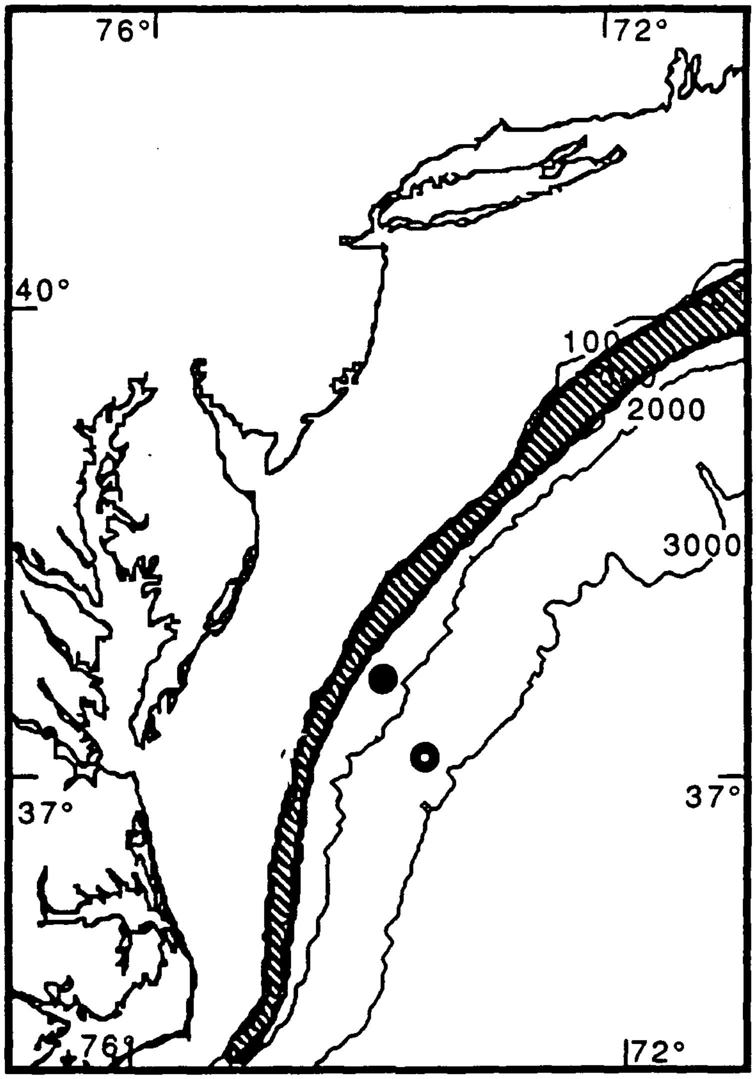



Figure 8. Winter distribution of Atlantic mackerel, *Scomber scombrus* (after CEQ/CZM, 1980).

Spiny Dogfish

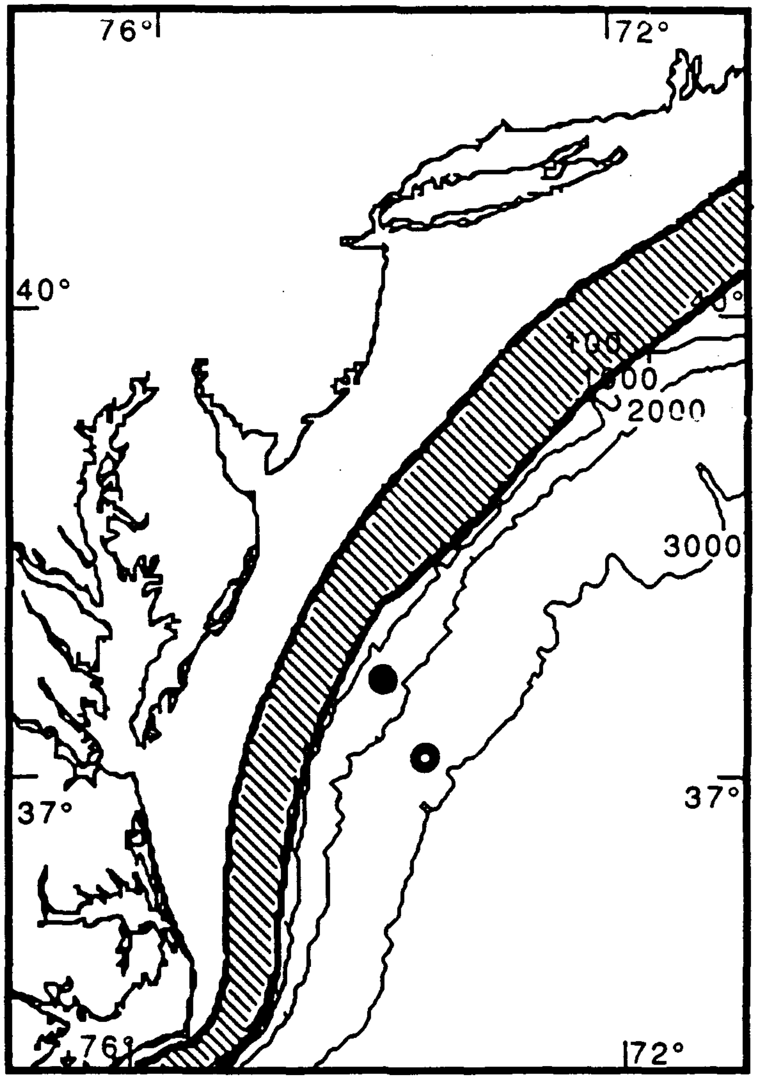



Figure 9. Winter distribution of Spiny dogfish, *Squalus acanthias* (after CEQ/CZM, 1980).

Table 2. Expected average school size and density for a 100 km x 100 km block of ocean surface centered at the near-shelf and off-shelf ARSRP sites.

| Species Group | Density in school (no./$m^2$) | School Size: Area ($m^2$) | School Size: Radius (m) | Ind. per School | Schools per 100 km x 100 km Block: near-shelf | Schools per 100 km x 100 km Block: offshelf |
|---|---|---|---|---|---|---|
| Mesopelagics | 60 | 490 | 13 | 30000 | 350000 | 350000 |
| Hake | 0.04 | $10^7$ | 1800 | 400000 | 30 | 3 |
| Atlantic herring | 5 | $2x10^6$ | 800 | $10^7$ | 4 | 0.4 |
| Bluefish | 23 | 2100 | 26 | 50000 | 22 | 2.2 |
| Butterfish | 130 | 400 | 11 | 50000 | 66 | 6.6 |
| Atlantic mackerel | 28 | 1800 | 24 | 50000 | 3600 | 360 |
| Spiny dogfish | 1 | 5000 | 40 | 5000 | 470 | 47 |
| Tuna | 1 | 2000 | 25 | 2000 | 0.41 | 0.41 |
| Swordfish | 0.0001 | $5x10^6$ | 1300 | 500 f | 9 | 9 |
| Porpoise | 0.0001 | 80000 | 160 | 8 | 380 | 380 |
| Pilot Whale | 0.0001 | $10^5$ | 180 | 10 | 43 | 43 |
| Sperm Whale | 0.0001 | 10000 | 56 | 1 | 10 | 10 |

Pacific hake *Merluccius productus* show they can be found in large shoals at constant depth extending offshore beyond the shelf break for several km over bottom depths up to 2000 m (Alverson and Larkins, 1969). Atlantic species of hake could also behave in such a manner. If so, then they would be expected in the vicinity of the ARSRP sites. Hake are generally loosely dispersed with roughly 400,000 fish occurring in a layer of 10 $km^2$ area (Alverson and Larkins, 1969; Boudreau and Dickie, 1987). Based on the foregoing observations, hake were assumed to occur at the ARSRP sites in 20 to 400 m depth at night and at 400 to 600 m depth during the day. The size distribution of hake was estimated using a yearly mortality rate of 35 % (NOAA, 1989) with fish lengths interpolated from the size of silver hake, as representative of all hakes, with 1 year old fish at 25 cm length and 6 year old fish at 50 cm length (Bigelow and Schroeder, 1953).

Butterfish are pelagic fish, spawning in inshore waters during summer and migrating to the warmer waters occurring at the edge of the continental shelf in winter over bottom depths of 300 m (NOAA, 1989) and, presumably, deeper. They inhabit near surface waters from the surface down to about 100 m (Bigelow and Schroeder, 1953). Butterfish are small, ranging in size from 10 to 34 cm with the mode of the mature swimbladder-regressed adults at about 20 cm. Based on anecdotal information from fisheries literature, boat captains, and biologists, butterfish schools are probably flat ellipsoids containing about 50,000 fish extending over about 400 $m^2$ (Table 2).

Atlantic mackerel are pelagic fish, spawning in inshore waters during summer and migrating to the warmer waters at the edge of the continental shelf in winter (NOAA, 1989). They are the most abundant commercial species in the region (NOAA, 1989) and occur in large schools at a wide range of depths from the surface to 200 m over bottom depths down to at least 1000 m. Atlantic mackerel range in size from 10 to 65 cm with the mode at about 25 cm (Bigelow and Schroeder, 1953). The areal extent of an Atlantic mackerel school is not well known. Using an approximate school size of 50,000 fish (Radakov, 1973), and assuming a flat disc shaped school 1 m thick with each fish occupying a volume equal to its body length cubed (Pitcher and Partridge, 1979) the typical school would extend over about 1800 $m^2$ (Table 2).

Spiny dogfish are very abundant and occur everywhere on the continental shelf. They are presumed to move towards the warmer waters of the shelf edge during winter (NOAA, 1989). They are regularly caught in otter trawls over bottoms of 300 m at the shelf edge. Because they feed on a variety of pelagic prey including squid and fish, they presumably could occur farther off the shelf during winter. Spiny dogfish range from 15 to 115 cm length with a modal size of about 50 cm (Bigelow and Schroeder, 1953). Dogfish occur in schools of many thousands of fish (Bigelow and Schroeder, 1953), with 5000 fish a rough guess of typical school size. Assuming a loose aggregation of 1 fish per square meter, such a school would extend over 5000 $m^2$.

Stock sizes in weight of these six commercial fish groups (Table 1) were converted to population numbers using the expected weight of the modal length of each species determined from length-weight relationships given by Wilk et al. (1978). Fish densities were obtained by dividing the assessed population numbers by the known winter habitat areas as determined from species distribution maps (Fig. 4 through 9). Because hake, herring, bluefish, butterfish, mackerel, and dogfish are primarily shelf species with offshore excursions expected but not documented, a modest 10% of their shelf density was assumed appropriate for the near shelf experimental site (Table 1), and 1% as appropriate for the off-shelf site. Finally, for the demersal species, hake and dogfish, densities were reduced by an additional 50% to account for some proportion of the population being well below the operating depths of the experiment. Hake were assumed to be present only at night.

Open Ocean Pelagic Stocks

Abundance estimates of wide ranging large pelagic fish were based on stock assessments by the International Commission for Conservation of Atlantic Tuna (ICCAT, 1989). Fish distributions were ascertained from a data base of swordfish logbook records for 1987 to 1989, provided by the NMFS, Southeast Fisheries Center, Miami, FL. The swordfish fishery uses longlines and operates over a large area of the northwest Atlantic, reporting catches of all large pelagic fish to NMFS. Four swimbladder-bearing species, bluefin tuna, *Thunnus thynnus*; yellowfin tuna, *Thunnus albacares*; albacore, *Thunnus alalunga*; and swordfish, *Xiphias gladius*, are reported from the vicinity of the experimental sites during the months of January through April. This is exemplified by catch records for bluefin tuna (Fig. 10), which show the association between these large pelagic predators, the shelf break, and the Gulf Stream. These fish are all warm temperate/tropical species migrating thousands of kilometers on a seasonal basis (Casey et al., 1987). Whether or not they are present during midwinter in any particular year will depend on hydrographic conditions. The remaining 50 to 75% of the longline catch is nonswimbladder

Bluefin Tuna Catch: January-April

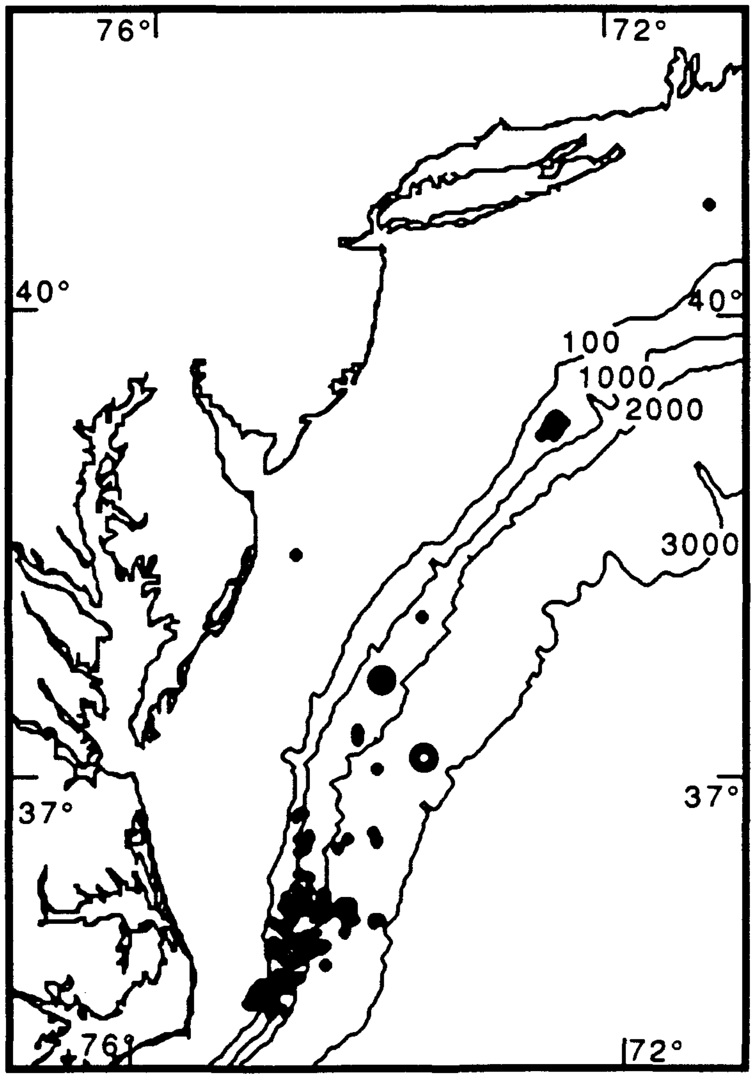



Figure 10. Distribution of longline by-catch of bluefin tuna, *Thunnus thynnus* during January to April 1987 - 1989.

bearing, nonschooling sharks, primarily blue shark, *Prionace glauca* (Casey et al., 1987), which are poor low frequency acoustic targets.

ICCAT (1989) has estimated the total swordfish population in the northwest Atlantic at 950,000 fish for 1987-1988, based on an analysis of population demography. Fisherman catch about 46,000 fish each year. By knowing the proportion of these fish that are caught within a hypothetical 100 km x 100 km square block surrounding the ARSRP site, and correcting for the catch efficiency of longline sets inside and outside this 100 km square, a rough estimate of 4300 fish, or 0.43 fish/$km^2$ can be "apportioned" to occur within the square. This estimate assumes that for swordfish, the fisherman are "wise", and their catch represents the true distribution of fish.

For bluefin tuna, the fishery is presently closed in the northwest Atlantic. However, some fish are accidentally caught, indicating that bluefin tuna are present near the experimental sites during midwinter (Fig. 10). Apportioning the ICCAT (1989) population estimate of 310,000 bluefin, gives an estimate of 0.07 bluefin/$km^2$ in the 100 km square that includes the experimental sites. This is likely an overestimate because the longline fishery is directed at swordfish rather than bluefin tuna. The swordfishery appears to have caught proportionately too many bluefin tuna within the 100 km square compared with the remainder of the northwest Atlantic.

Population assessments were not available from ICCAT for yellowfin and albacore. Instead, for nontarget catch such as albacore, the overall catch rate for bluefin tuna (number caught/number present) was used to estimate the population size of albacore at 240,000 fish. For yellowfin, which is a target species, the catch rate for swordfish was used to estimate the population of yellowfin at 310,000 fish. From these approximate population estimates, longline catch records were used to apportion yellowfin and albacore to the 100 km square block that includes the experimental sites. This gave 0.008 and 0.005 yellowfin and albacore per $km^2$, respectively. Overall, swordfish (0.43 ind./$km^2$) are expected to be more abundant than all tuna (0.08 ind./$km^2$).

Swordfish roam over a wide range of depths from near the surface to 600 m. They are active near the surface at night and descend to greater depths during day. However, in the cold slope water, they are likely to remain in the upper 150 m during both night and day (Carey and Robison, 1981). Swordfish in the northwest Atlantic range from 65 to 210 cm lower jaw fork length with the mode at about 115 cm (ICCAT, 1989).

Swordfish are expected to occur in loose aggregations of about 500 fish with about 100 m between individuals (Nakamura, 1967; Ovchinnikov, 1970). Such aggregations would occupy an area of about 5 $km^2$ (Table 2).

Since bluefin tuna are likely to be by far the most abundant tuna encountered, their characteristics were used for all tuna. Bluefin can be considered a near-surface predator, occurring within 50 m of the surface. In the northwest Atlantic, their size ranges from 56 to 279 cm with 64% between 50 and 100 cm length (ICCAT, 1989). Bluefin schools will typically contain 2000 fish with each fish occupying about 1 $m^2$ (Nakamura, 1967; Ovchinnikov, 1970), giving a school area of about 2000 $m^2$ (Table 2).

Mesopelagics

Mesopelagic fish species are generally too small for their swimbladders to resonate at ARSRP frequencies. However, Rayleigh scattering from their swimbladders will produce low volume reverberation levels at these frequencies. Since populations of these fishes are found virtually everywhere over deep oceanic waters, scattering from them can be expected to set the lower bound in instances where larger fishes are not present. Hence, population characteristics of these fishes near the experimental sites are of interest.

The density, size, and depth ranges of mesopelagic fish were obtained from midwater trawls in the slope water of the North Atlantic (R. H. Love, unpublished data) during June 1978 at a location approximately 160 km northeast of the near-shelf site. Average densities, expressed as number per square meter of ocean surface, were approximately 1 ind./$m^2$ from 0 to 400 m. This value was used for both the near-shelf and off-shelf sites. These densities are, incidently, the same as those obtained by Backus et al. (1970) for the slope water. The mesopelagic fauna was dominated by 70 % *Hygophum hygomii*, which were small, ranging from 25 to 50 mm length and found from the surface to 50 m at night and absent from the upper 600 m by day. The remaining 30% of the mesopelagics were mostly 6 other species ranging in size from 10 to 70 mm and found from the surface to 200 m depth at night and absent from the upper 600 m by day.

Mesopelagic fishes may also occur at higher than average densities. Backus et al. (1968) encountered excessively high *Ceratoscopelus maderensis* abundances of 10 to 100 ind./$m^2$ in the slope water during the fall of 1967.

Every several years, large congregations of these fish occur in the slope water. The periodicity, mechanisms, and ecological significance of these accumulations are unknown (J. Craddock, Woods Hole Oceanographic Institution, Woods Hole MA, pers. comm.). They occur in schools roughly 6 m thick and 13 m radius (Backus et al., 1968). At densities of 10 ind./$m^2$, schools would contain about 30,000 individuals (Table 2).

Marine Mammals

Marine mammal abundance data are available directly from CETAP (1982). CETAP (1982) converted sightings per mile of transect traveled to numbers per unit area, based on assumptions of the observer's field of view and the amount of time each species spends at the surface. Along the shelf edge and slope during winter, the most abundant species (as ind./$km^2$ and length) are the saddleback dolphin, *Delphinus delphis* (0.25, 2 m); pilot whale, *Globicephala* spp. (0.043, 6 m); bottlenose dolphin, *Tursiops truncatus* (0.024, 3 m); and striped dolphin, *Stenella coeruleoalba* (0.017, 2 m). Other less abundant species are grampus, *Grampus griseus* (0.006, 3 m) and sperm whale, *Physeter catodon* (0.001, 20 m). Based on this data, small porpoise and whales of 2 to 4 m length are most abundant at 0.3 ind./$km^2$. Intermediate size whales of 4 to 10 m length are less abundant at 0.04 ind./$km^2$ and large whales greater than 10 m are least abundant at 0.001 ind./$km^2$. All marine mammals are considered near-surface scatterers occurring within 100 m of the surface.

Porpoise and whales often occur in pods. Observations of modal pod size from CETAP (1982) indicate small porpoise and whales occur at 8 individuals per pod, medium sized whales at 10 individuals per pod, and large whales as single individuals (Table 2). Anecdotal observations indicate animals that would be about 100 m apart and pods would range from 10,000 to 100,000 $m^2$ (Table 2).

Oceanographic Variability

Strong hydrographic events occurring near the ARSRP sites will certainly bring about changes in animal numbers. The most probable occurrence would be the passage of a warm core ring through the area. Many marine animals associate with frontal boundaries (Brandt and Wadley, 1981; Nero et al., 1990) but whether large fish or marine mammals associate with the peripheral fronts of rings is not known for certain. However, fish such as swordfish have been observed following deep thermal features, presumably in pursuit of prey (Carey and Robison, 1980). Therefore, the passage of the peripheral edge of a ring through the ARSRP site could carry with it greater fish densities.

Strong seasonal anomalies may also influence expected biological activity off the shelf. In an average winter, warm surface waters lie just southeast of the ARSRP sites (Fig. 3). Bluefin tuna are typically found at temperatures as low as 12°C and would likely frequent the ARSRP site. Swordfish are found at somewhat higher temperatures ≈20°C. During a slightly warmer winter, large pelagics such as tuna and swordfish would be more abundant than predicted. Likewise, during an unusually cool winter, these large pelagics would be absent.

## BIOACOUSTIC MODELING

### Individuals

All swimbladder-bearing fish were modeled as reverberant scatterers using the model of Love (1978) and the information given above. Each fish was assumed to have a spherical swimbladder with a radius equal to some proportion of fish length, as estimated from measurements of fish swimbladders. Values of swimbladder radius to fish length used in the model were: mesopelagics 0.03 (data in Goodyear et al., 1972); hake, herring and bluefish 0.044 (teleosts in general, Love, 1978); and tuna and swordfish 0.066 (measurements taken from Chang and Magnuson, 1968). Mesopelagics and hake have closed swimbladders and actively pump gas in or out to maintain them at constant volume with depth. Herring swimbladders are open to their digestive tracts. They adjust their swimbladder volume by swallowing air at the surface and passing it to their swimbladder. Their swimbladders were assumed to be at equilibrium at 40 m and to compress following Boyle's Law below that depth. Swordfish ascend and descend so rapidly (Carey and Robison, 1980), that their swimbladders are believed to be at equilibrium at about 10 m and compress below that depth. Tuna and bluefish are found over a small depth range (0-50 m) and their swimbladders were assumed to remain at constant volume with depth.

Nonswimbladder-bearing fish were modeled using Stanton's (1989) model for a fluid filled prolate spheroid. Spheroids were given minor axis lengths of 10 % of fish length. Values used for the ratio of speed of sound in the fish to that of water of 1.052 and for the ratio of the density of fish to that of water of 1.043 fall at the midpoints of the ranges of values reported for fish by Clay and Medwin (1977).

Because of their large size, marine mammals were considered as geometric scatterers over the 100 Hz to 1000 Hz frequency range. Rough approximations of side-aspect target strength were made based on actual target strength measurements of live whales (Dunn, 1969; Love, 1973; Levenson, 1974). These were adjusted to the average length of the most common species, porpoise (2-4 m), medium whales (4-10 m), and large whales (10 m) to give target strengths of -15, -5, and 0 dB respectively.

Uniform Layers

Volume scattering strengths of a uniform layer of animals were calculated based on average areal densities of the animals. The average layer strength ($S_L$) of each species or species group is

$$S_L = TS_i + 10 \log N,$$

where $TS_i$ is the target strength of an individual at a given frequency, and N is species abundance in ind./$m^2$. Total average layer strengths were calculated as the exponential sum of the average layer strengths of all species present.

Schools and Pods

All of the species under consideration aggregate to some degree. The impact of patchiness or aggregation was evaluated by first estimating the frequency of occurrence of schools or pods of different species in an area surrounding the experimental sites and then calculating the target strengths of the schools and pods.

Prediction of school size, density of fish within schools, and number of schools is difficult because of myriad factors which influence fish schooling. All are dependent on fish behavior as influenced by age, spawning, migration, feeding, hydrographic conditions and the presence of predators (Pitcher, 1986). Since knowledge of patchiness and schooling for fish is sparse, best guesses of "average" schools from the literature were used to estimate the number of such schools of each species or species group occurring within a 100 km square around the experimental sites (Table 2).

Because pods of marine mammals can be observed at the surface, reasonable estimates of pod size and spacing are available. Modal size of marine mammal pods were obtained from surface sightings (Table 2).

Using these estimates of pod and school densities, calculations of the probability of a 1 second sound pulse from the ARSRP array encountering a biological target between ranges corresponding to 12° and 2° grazing angles were made. Encounter probabilities were determined from an equation of random search (Koopman, 1956), where the probability of encountering a single target $P_1$, on a single ping is:

$$P_1 = \frac{A_d + A_s}{A_o},$$

when searching operating area $A_o$ with detection area $A_d$ and school size $A_s$. $A_d$ for grazing angles between 12° and 2° is about 100 $km^2$, which is 10 times larger than the largest fish schools (Table 2). Thus $A_s$ is negligible for most calculations.

For n repeated chances of encountering m targets, the probability of encountering one or more targets is:

$$P_{n,m} = 1 - (1 - P_1)^{(n \times m)},$$

where each chance of encountering a target is assumed to occur independently and randomly for each group of transmitted pulses. Since pulses are transmitted at 1 hour intervals the assumption of independent looks is not valid for smaller, slow swimming fish. However, this equation is sufficient for present estimates.

No models exist for estimating target strengths of schools of fish near swimbladder resonance. Love (1981) has developed a model that gives realistic estimates of target strengths in the geometric region well above resonance. This model assumes that the target strength of a school of fish ($TS_s$) is

$$TS_s = TS_i + 10 \log F_i,$$

where $F_i$ is the number of fish insonified when multiple scattering and attenuation through the school are taken into account. The model shows that essentially all fish in small loose schools are insonified and that as the schools get larger and denser proportionately fewer fish are insonified. Present calculations assume that

$$TS_s = TS_i + 10 \log F_s,$$

where $F_S$ is the number of fish in the school. Although this equation overestimates school target strengths for large schools such as Atlantic herring and hake, it provides an upper limit that is adequate for present purposes.

Pods of marine mammals are usually loosely aggregated. Therefore, the above equation should provide a good estimate of pod target strengths.

## RESULTS

### Volume Reverberation

The effects of volume reverberation at the ARSRP sites were determined by estimating average layer strengths for each species or species group and for all species at each site. Results for the near-shelf and off-shelf sites are shown in Figures 11 and 12, respectively.

Figure 11 shows that at night at the near-shelf site, total average layer strengths for the upper 200 m are expected to be -53 dB at 800 Hz and gradually decline to -64 dB at 100 Hz. Bluefish, hake, and herring are expected to contribute most to layer strengths between 70 and 2000 Hz. Porpoise and whales combined will contribute approximately -76 dB over the 20 to 5000 Hz range. This level forms a general baseline for the lowest expected layer strengths in the absence of shelf/slope species at frequencies below 1000 Hz. Larger pelagic fish such as swordfish and tuna will only contribute at levels equal to the marine mammals in the 20 to 100 Hz range, raising layer strengths to -72 dB at 40 Hz. Mesopelagic fish will begin to contribute to layer strength above 3000 Hz.

During day, total average layer strengths are expected to decrease substantially from those at night. These changes will be most pronounced between 700 and 800 Hz, where strengths decrease from -53 to -66 dB because of the diurnal migration of herring and hake into deeper water (Fig. 11). Nonswimbladder bearing fish (dogfish, mackerel and butterfish) are not significant contributors to layer strengths below 5000 Hz. Butterfish are not shown in Figure 11 because their levels are less than -90 dB.

At the off-shelf site, abundances of the primary shelf species, herring, bluefish and hake were assumed to be one-tenth of those at the near-shelf site, resulting in a 10 dB drop in their contributions to total average layer strengths. As shown in Figure 12, this results in night layer strengths of -63 dB at 800 Hz and -71 dB at 100 Hz. During the day, off-shelf layer strength is expected to be even lower, at -68 to -74 dB over the 100 to 800 Hz range.

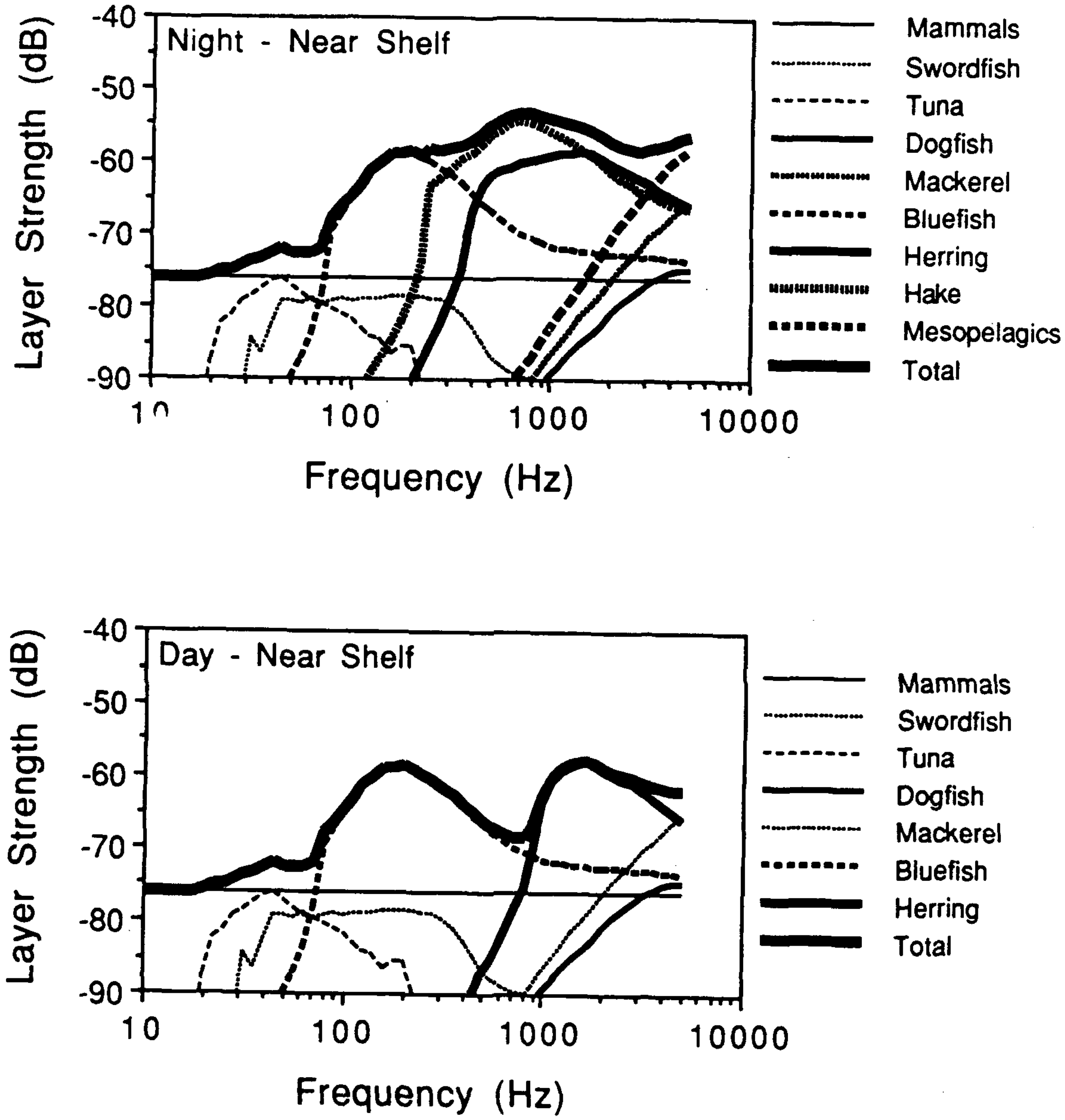
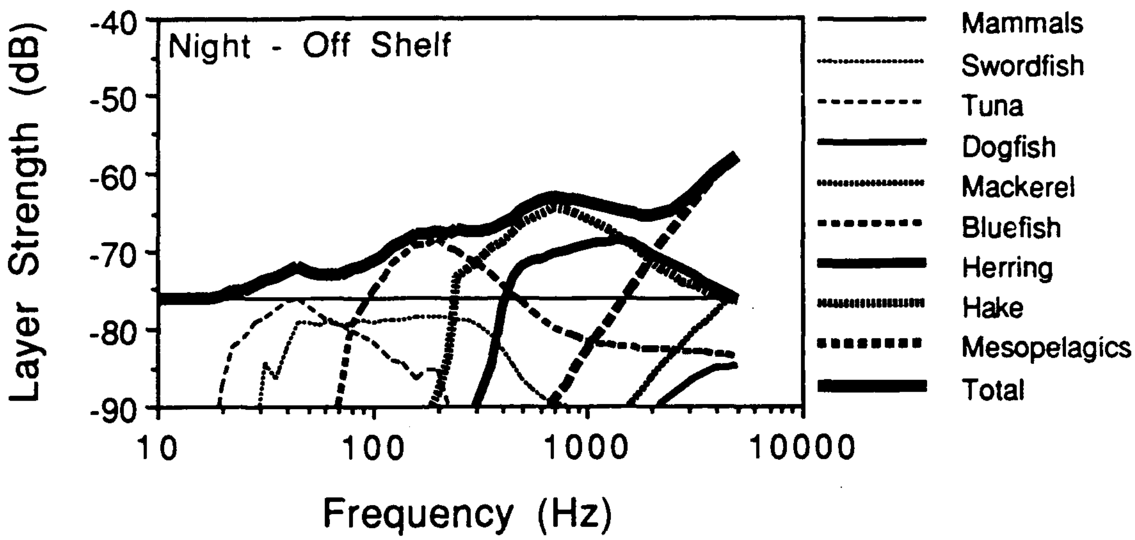



Figure 11. Layer strengths predicted from average midwinter densities of fish and marine mammals at the near-shelf ARSRP site.



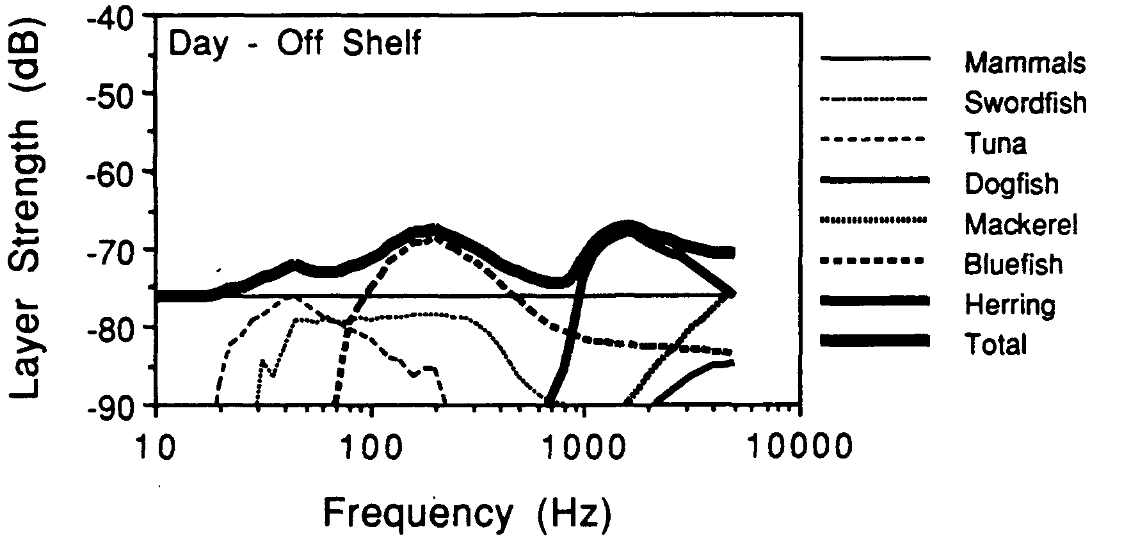




Figure 12. Layer strength predicted from average midwinter densities of fish and marine mammals at the off-shelf ARSRP site.

## Clutter and Discrete Echoes

Accurate predictions of clutter and discrete echoes depend on schooling information that is not available. Present biological knowledge allows only rough estimates of school and pod numbers and target strengths to be made. Hence, calculations of numbers of schools and pods have been based on a single "average-size" school or pod for each species. Also, models that predict upper limits of target strength were deemed adequate and school target strengths were determined using the maximum individual fish target strengths in the 100 to 800 Hz frequency range.

Figure 13 shows the results of the target strength calculations. Chance of encounter was assumed to be directly proportional to the number of schools or pods even though some fish would be below the depth range of the ARSRP array during the day. There is a general inverse relationship between target strength and the number of schools and pods.

Since determining the transition from reverberation to clutter to discrete echoes is subjective, interpretation of Figure 13 is also subjective. Two effects are undisputable: (1) mesopelagics are so numerous that they will certainly produce reverberation; and (2) herring, bluefish, hake, and tuna schools, that have high target strengths and low numbers will, statistically, produce discrete echoes every several hours to several days. Target strengths and numbers of swordfish schools and whales are probably high enough to cause a discrete echo every hour or two. Pods of porpoise will probably be the primary cause of clutter, although they could be numerous enough to produce reverberation. Schools of nonswimbladder bearing fish have low target strengths and will contribute to clutter or reverberation. These statements are based on average schools and pods; actual distributions of school or pod size and density will further blur the indistinct boundaries between reverberation, clutter, and echoes.

# DISCUSSION

The results shown in Figure 13 indicate that one target with target strength of 0 dB or higher will probably be encountered on every set of ARSRP array transmissions. Since the dimensions of the targets are small relative to those of the insonified region, these targets generally will not contribute to average layer strengths as shown in Figures 11 and 12. Figure 13 indicates that only pods of porpoise and schools of mesopelagics and nonswimbladder-bearing fish are possibly numerous enough to contribute to average layer strengths. Figure 14 shows average layer strengths

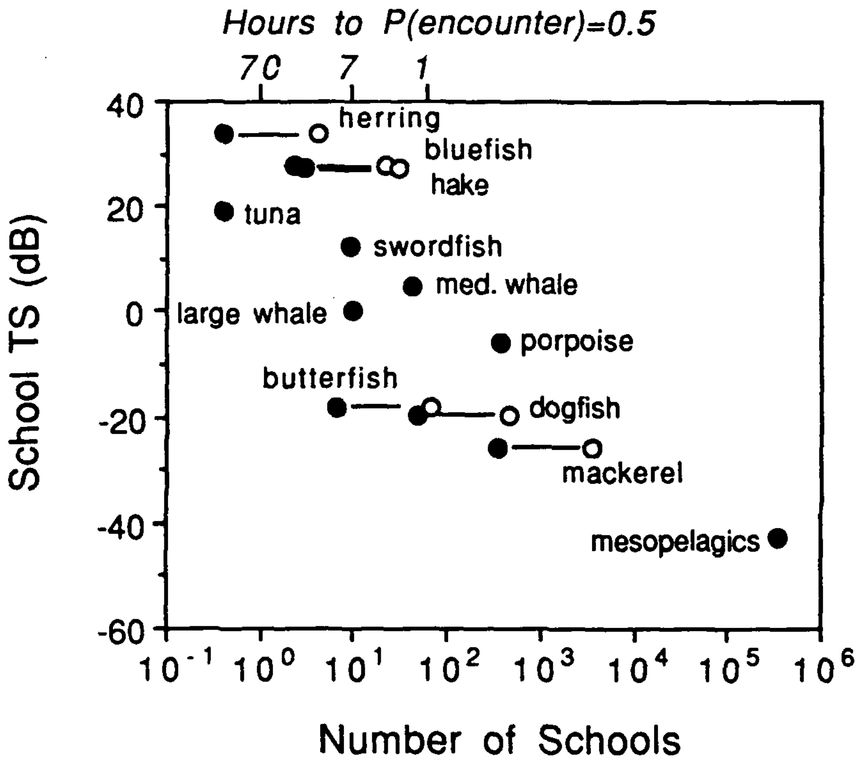



Figure 13. Expected number of fish and marine mammal schools at the two possible ARSRP sites and their potential school target strength. For those groups with two estimates, ● - indicates estimates for off-shelf sites and O - indicates estimates for near-shelf sites.

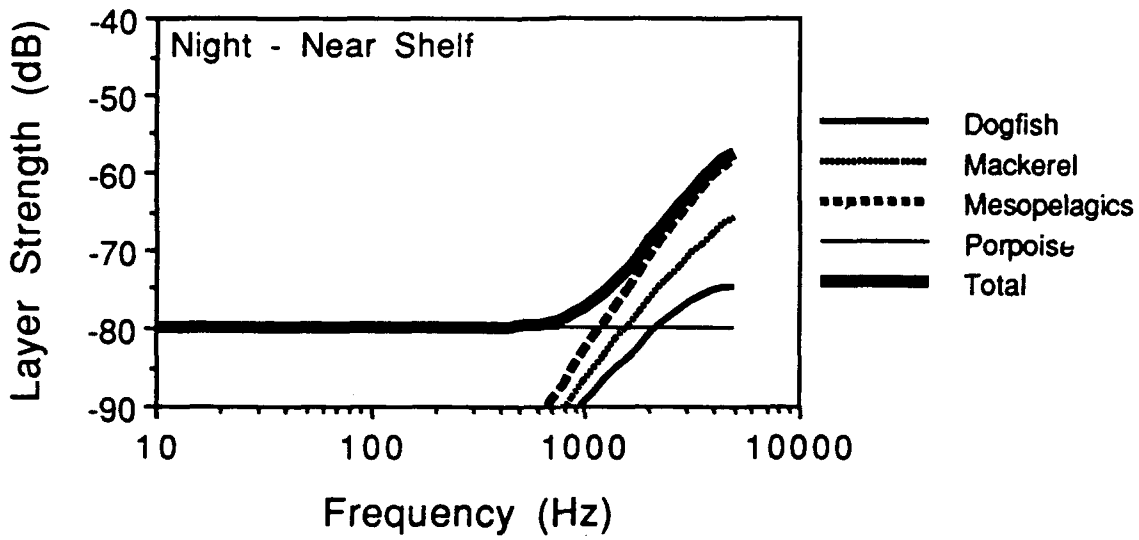



Figure 14. Layer strength predicted from average densities of species most likely to contribute to average volume reverberation at night at the near-shelf ARSRP site.

attributed to these species at the near-shelf site at night. In the 100 to 800 Hz range, only porpoise are significant.

Actual distributions of individuals and groups, although unknown, are certain to be nonuniform. Animals, particularly the fish, are more likely to be concentrated in one or a few areas and absent from others at a given moment. These concentrations will migrate depending on the behavioral characteristics of the particular species. Thus, values higher or lower than the "average" limits of Figure 15 can be expected. As animals concentrate in certain areas the layer strength will increase, while in other areas it will decrease: Example A - if 90% of the scatterers occur in 50% of the area, the layer strength in that area will be 2.6 dB higher than that based on average densities, while in the remaining 50% of the area it will be 7 dB lower; Example B - if 95% of the scatterers occur in 10% of the area, the increase will be almost 10 dB, while the decrease in 90% of the area will be 13 dB. Given that several species are generally involved, Example A is possible, while Example B seems extreme. Therefore, it is believed that the "average" limits of Figure 15 provide reasonable working limits on expected volume reverberation.

The curves in Figure 15 demonstrate the wide variability that may occur at different site locations due to variations in animal distribution. The curves easily encompass volume scattering strengths measured by Chapman et al. (1974) and (R. H. Love, unpublished data) at nearby locations, as shown in Figure 16. Measured strengths are within 5 dB of present predictions, except at frequencies above 3000 Hz, where Chapman's values are significantly higher. This is presumably due to a greater number of mesopelagic fish than were accounted for based on densities estimated from various trawl surveys (Backus et al., 1970; R. H. Love, unpublished data). One possibility is that at the time of Chapman's work, *Ceratoscopelus maderensis* were at a peak in their abundance (Backus et al., 1968).

Total average layer strengths are directly comparable to surface scattering strengths. Hence, they are useful in determining the potential effects of volume reverberation on surface scattering measurements. Total average layer strengths from Figure 15 are compared to potential surface scattering strengths in Figure 17. Potential surface scattering strengths were calculated for the 10 to 5000 Hz frequency range for wind speeds of 10 and 20 kt and grazing angles of 2° and 12° using the relationship described by Chapman and Harris (1962). Clearly, near surface volume reverberation can interfere with measurements of surface scattering at low grazing angles. Because fewer biological scatterers occur offshore, volume rever-

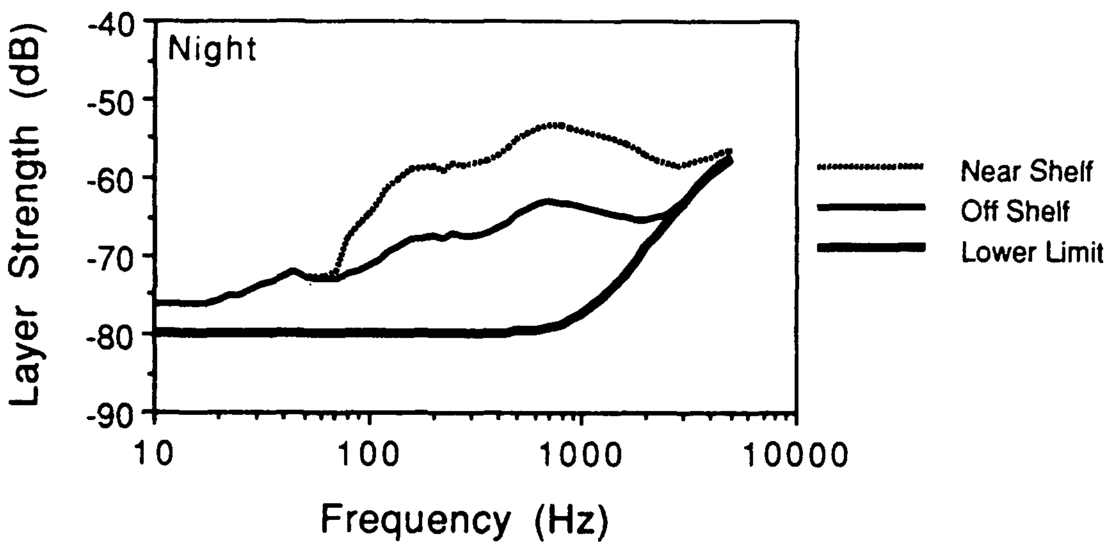



Figure 15. Probable limits of volume reverberation at night at the ARSRP sites.

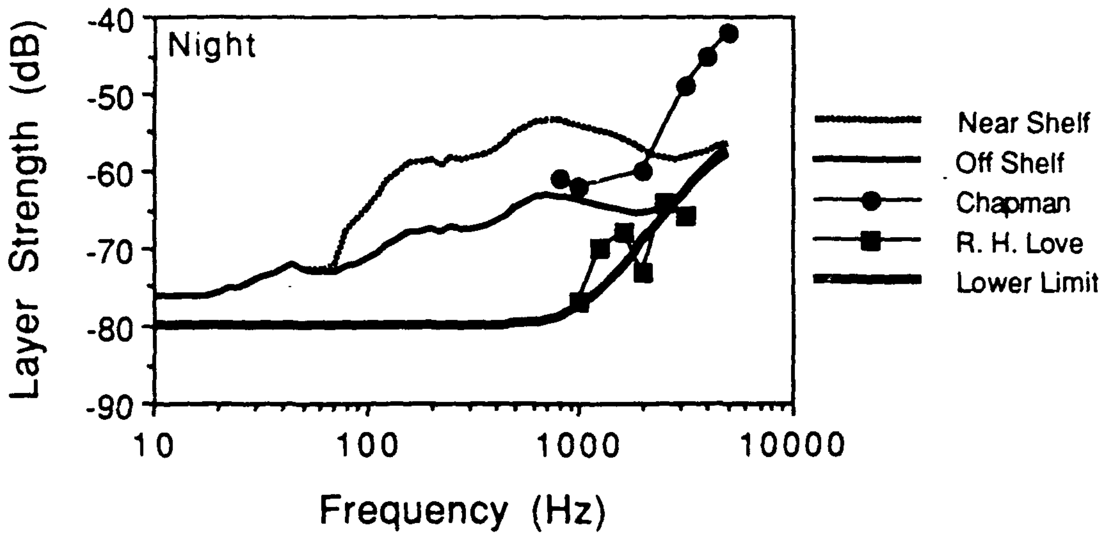



Figure 16. Comparison of estimated limits of volume reverberation with direct measurements over the 0.8 kHz to 5 kHz range by Chapman et al. (1974) and R. H. Love unpublished data.

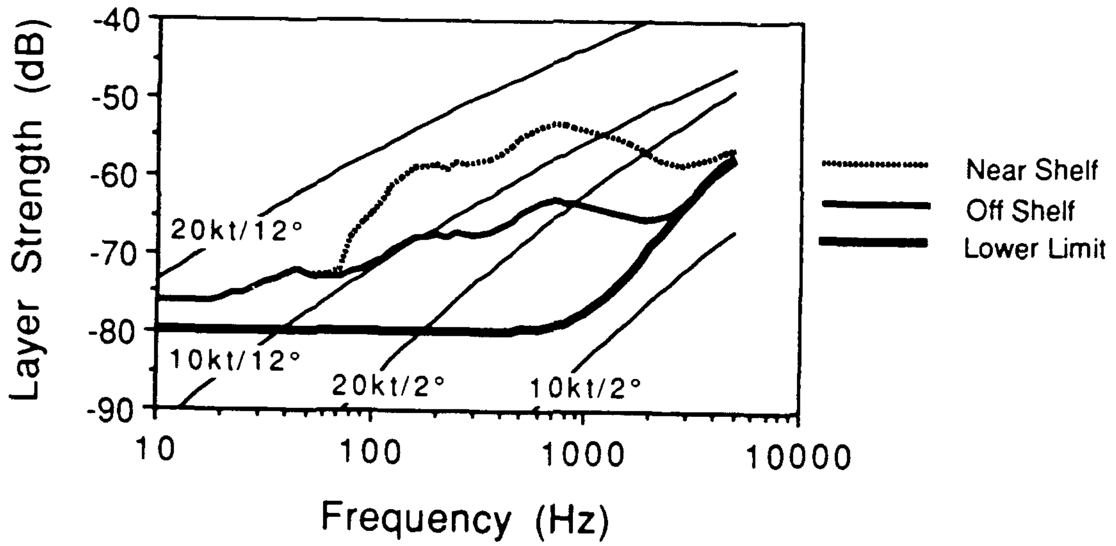



Figure 17. Comparison of limits of volume reverberation with estimates of surface scattering strength from Chapman and Harris (1962).

beration will be less at the off-shelf site than at the near-shelf site. Diurnal migrations will result in lower volume reverberation at both during day.

Fortunately, the most numerous large fish at this particular experimental site, Atlantic mackerel, *Scomber scombrus*, do not possess swimbladders. If they did, average volume reverberation between 100 and 800 Hz would be as high as -44 dB at the near-shelf site and -54 dB at the off-shelf site. Such high levels would interfere with all measurements of surface scattering except those at the highest wind speeds and steepest grazing angles (Fig. 17). In other parts of the world, other species occurring in high numbers, including other mackerel species, such as Pacific mackerel, *Scomber japonicus*, do possess swimbladders (Magnuson, 1973) and could interfere significantly with surface scattering measurements.

## SUMMARY

Acoustic models were used to estimate volume scattering from average numbers of animals for two sites off the Virginia coast as part of planning for the ONR ARSRP sea surface scattering experiment. Animal densities were derived from fisheries assessments and airborne surveys of marine mammals. Target strengths were based on: resonant models of fish with swimbladders; bent cylinder models of fish without swimbladders; and in situ measurements of mammals.

Average layer strengths calculated for average densities of animals at the two potential experimental sites ranged from -74 to -53 dB between 100 and 800 Hz. Since most fish and marine mammals will be aggregated to some degree, volume scattering can be expected to vary within the area insonified by the ARSRP array. A model of fish school encounter suggests that only aggregations of porpoise, mesopelagic fish and nonswimbladder bearing fish are widespread enough to produce consistent reverberation, producing layer strengths slightly above -80 dB. Given the variations with frequency, location, time of day, and uncertainties of animal distribution, layer strengths at the experimental sites are expected to be between -80 and -50 dB. The fish school encounter model also suggests that target strengths and numbers of swordfish schools and whales are high enough to cause a strong discrete echo every several hours; while herring, bluefish, hake, and tuna schools will cause discrete echoes at time scales of hours to days.

Estimates of surface scattering based on relationships reported by Chapman and Harris (1962) show that at particular frequencies, times and locations, biological scattering will interfere with measurements of surface scattering at shallow grazing angles.

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**3. Report Type and Dates Covered.** Final

**4. Title and Subtitle.**
An Assessment of Near Surface Biological Volume Scattering off the Continental Shelf of Virginia

**5. Funding Numbers.**
*Program Element No.* 0601153N
*Project No.* 03204
*Task No* 040
*Accession No.* DN250049

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**8. Performing Organization Report Number.**
NOARL Technical Note 144

**9. Sponsoring/Monitoring Agency Name(s) and Address(es).**
Office of Naval Research
800 N. Quincy Street
Arlington, VA 22217-5000

**10. Sponsoring/Monitoring Agency Report Number.**
NOARL Technical Note 144

**11. Supplementary Notes.**

**12a. Distribution/Availability Statement.**
Approved for public release; distribution is unlimited.

**12b. Distribution Code.**

**13. Abstract (Maximum 200 words).**

Acoustic models were used to estimate volume scattering from fish and marine mammals in the vicinity of the Surface WAves Dynamics Experiments (SWADE) at 37.5 N and 74 W as part of planning for the Office of Naval Research Acoustic Reverberation Special Research Project (ARSRP) sea surface scattering experiment. Animal densities were derived from fisheries assessments and airborne surveys of marine mammals. Animal target strengths were based on resonant models of fish with swimbladders, bent cylinder models of fish without swimbladders, and in situ measurements of mammals. Estimates of scattering were made for a broad frequency range of 10 Hz to 10 kHz with emphasis placed on the planned experimental frequencies of 100 Hz to 800 Hz. Average layer scattering strengths calculated for average densities of animals at two potential experimental sites ranged from -74 to -53 dB between 100 and 800 Hz. Since most fish and marine mammals will be aggregated to some degree, volume scattering can be expected to vary within the area insonified during ARSRP measurements. A model of fish school encounter suggests that only aggregations of porpoise, mesopelagic fish and nonswimbladder bearing fish are widespread enough to produce consistent reverberation, producing layer strengths slightly above -80 dB. Given the variations with frequency, location, time of day, and uncertainties of animal distribution, layer strengths at the experimental sites are expected to be between -80 and -50 dB. The fish school encounter model also suggests that target strengths and numbers of swordfish schools and whales are high enough to cause a strong discrete echo every several hours; while herring, bluefish, hake, and tuna schools will cause discrete echoes at time scales of hours to days. Estimates of surface scattering based on relationships reported by R.P. Chapman and J.H. Harris (1962, *Surface backscattering strengths measured with explosive sound sources.* J. Acoust. Soc. Am. 34:1592-1597) indicated that near surface biological scattering will interfere with measurements of surface scattering at shallow grazing angles.

**14. Subject Terms.**
Biological Scattering, Volume Reverberation

**15. Number of Pages.** 43

**16. Price Code.**

**17. Security Classification of Report.** Unclassified

**18. Security Classification of This Page.** Unclassified

**19. Security Classification of Abstract.** Unclassified

**20. Limitation of Abstract.** SAR